

EXPRESS MAIL NO. EV343427580US

DATE MAILED: JULY 18, 2003

INVENTORS: Francesco PAPPALARDO and Agatino PENNISI

5

PIPELINE STRUCTURE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon and claims priority from European Patent Application No. 02425469.0, filed July 19, 2002, the entire disclosure of which is herein
10 incorporated by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to digital systems, and more specifically to a
15 pipeline structure for use in a digital system.

2. Description of Related Art

A pipeline structure consists of a sequence of functional units (stages), which perform a task in several steps; the stages work in parallel thus giving higher throughput
20 than if all the steps had to be completed before starting a next task. Pipelines are commonly used in several applications, for example, to process different parts of an instruction in a microprocessor.

Typically, the pipeline has a synchronous architecture. A synchronous pipeline receives a single clock signal, which controls all the stages. As a consequence, every
25 stage must complete its work within one clock period.

A drawback of the synchronous pipeline is that all the stages switch at the same time. This involves high peaks of power consumption (due to the current dissipated by the short-circuits that are formed during the switching of the transistors of the logic gates,

EXPRESS MAIL NO. EV343427580US

and to the current needed for charging and discharging wires and capacitors). These peaks of power consumption introduce sources of noise, which can jeopardize the functionality of the whole electronic device that embeds the pipeline. Moreover, they impose several constraints in the design of a power supply structure; particularly, metal tracks used to supply the electronic device (when integrated in a chip of semiconductor material) must be dimensioned so as to withstand the aforementioned high peaks. As a consequence, an increased area of the chip is required to integrate the electronic device.

5

Asynchronous pipelines have been proposed in order to reduce the peaks of power consumption. In an asynchronous pipeline, all the stages proceed independently (so that 10 they do not switch at the same time). A handshaking mechanism is then used to maintain every pair of adjacent stages in synchronization. For this purpose, each stage generates a signal indicative of the completion of its work. This signal is used to move the result of the stage to a next stage, and then to trigger starting of the next stage.

However, the implementation of the handshaking mechanism is relatively 15 complex. Moreover, an additional circuit is required to synchronize the flux of input and output information with the external circuitry.

SUMMARY OF THE INVENTION

In view of these drawbacks, it is an object of the present invention to overcome 20 the above-mentioned drawbacks and to provide an improved pipeline structure.

Briefly, one embodiment of the present invention provides a pipeline structure for use in a digital system. The pipeline structure includes stages arranged in a sequence from a first stage for receiving an input of the pipeline structure to a last stage for providing an output of the pipeline structure. At least one intermediate stage is 25 interposed between the first stage and the last stage. The pipeline structure also includes a phase shifting circuit for generating at least one local clock signal for controlling the at least one intermediate stage. The first stage and the last stage are controlled by a main

EXPRESS MAIL NO. EV343427580US

clock signal, the at least one local clock signal is generated from the main clock signal, and the main clock signal and the at least one local clock signal are out of phase.

Moreover, embodiments of the present invention provide a digital system including such a pipeline structure, and an electronic device including such a digital system.

A further embodiment of the present invention provides a method of operating a pipeline structure that includes stages arranged in a sequence. The sequence includes a first stage for receiving an input of the pipeline structure to a last stage for providing an output of the pipeline structure, with at least one intermediate stage being interposed between the first stage and the last stage. According to the method, the first stage and the last stage are controlled with a main clock signal, and at least one local clock signal is generated from the main clock signal. The main clock signal and the at least one local clock signal are out of phase, and the at least one intermediate stage is controlled with the at least one local clock signal.

Other objects, features and advantages of the present invention will become apparent from the following detailed description. It should be understood, however, that the detailed description and specific examples, while indicating preferred embodiments of the present invention, are given by way of illustration only and various modifications may naturally be performed without deviating from the present invention.

20

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram of a hand-held computer in which the pipeline structure of the present invention can be used;

25 Figure 2 illustrates the functional blocks of a pipeline structure according to a preferred embodiment of the present invention; and

Figure 3 is a timing diagram showing operation of the pipeline structure of Figure 2.

EXPRESS MAIL NO. EV343427580US

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Preferred embodiments of the present invention will be described in detail hereinbelow with reference to the attached drawings.

Figure 1 shows a hand-held computer 100. The hand-held computer 100, also known as palmtop, pocket computer or Personal Digital Assistants (PDA), is a very small system that literally fits in one hand. The hand-held computer 100 is formed by several units, which are connected in parallel to a communication bus 105. In detail, a microprocessor 110 controls operation of the hand-held computer 100, a DRAM 115 is directly used as a working memory by the microprocessor 110, and a Read Only Memory (ROM) 120 stores basic code for a bootstrap of the hand-held computer 100.

Several peripheral units are further connected to the bus 105. Particularly, a non-volatile memory 125, typically consisting of a flash E²PROM, operates as a solid-state mass memory for the hand-held computer 100. Moreover, the hand-held computer 100 includes input devices 130 (for example, an electronic pen or stylus), and output devices 135 (for example, a flat panel screen made with a TFT technology). Interfaces 140 are used to connect external peripherals (such as a PCMCIA network card) to the hand-held computer 100.

A timing unit 145 generates a main clock signal CLK_m, which is used to synchronize operation of the hand-held computer 100. A battery pack 150 provides a power supply voltage Vdd for all the units of the hand-held computer 100, so as to enable the hand-held computer 100 to run without being plugged in.

The microprocessor 110 has a pipeline architecture, wherein a sequence of stages simultaneously processes different parts of every instruction to be executed by the microprocessor 110. Particularly, a first stage fetches the instruction (from the DRAM 115), a second stage decodes the instruction, a third stage fetches the arguments (if any), a fourth stage executes the operations required by the instruction, and a fifth stage stores a possible result. In this way, as one instruction is executed, the next instruction is being decoded and the one after that is being fetched. For maximum performance, the pipeline

EXPRESS MAIL NO. EV343427580US

requires a continuous stream of instructions; therefore, this technique is commonly combined with instruction prefetch in an attempt to keep the pipeline busy.

Similar considerations apply if the hand-held computer has a different structure or includes other units (for example, an infrared port), if the pipeline is formed by a different number of stages, if no prefetch is implemented, if each stage performs other functions, and the like. Alternatively, the pipeline is used in the microprocessor of a laptop computer, in a mobile telephone, in a memory (wherein data is saved in a stack while the next data is being accessed), or more generally in any other digital system.

Figure 2 shows a pipeline structure according to a preferred embodiment of the present invention for use in the microprocessor of the hand-held computer. The pipeline structure 200 is formed by $N=5$ stages ST_i (with $i=1\dots N$). Each stage ST_i includes a register R_i and a combinatorial circuit C_i (except for the last stage ST_5 , which only has the register R_5 without any combinatorial circuit). The combinatorial circuit C_i is cascade connected to the corresponding register R_i ; the register R_1 (of the first stage ST_1) and the register R_5 (of the last stage ST_5) define an input and an output, respectively, of the pipeline 200.

----- An input word IN (for example, of 32 bits) received by the pipeline 200 is stored in the register R_1 (as a word IN_1). Each register R_i (with the exception of the last one) operates as an input buffer for the corresponding combinatorial circuit C_i . The combinatorial circuit C_i processes a word IN_i provided by the register R_i , and generates a result consisting of a word OUT_i ; the combinatorial circuit C_i has a propagation time P_i (defined as the delay for obtaining the word OUT_i from the word IN_i). The output of the combinatorial circuit C_i is then stored in the next register R_{i+1} (so that $IN_{i+1}=OUT_i$). The word stored in the last register R_5 (OUT_4) is output as the output word OUT of the pipeline 200.

Operation of the pipeline 200 is controlled by the main clock signal CLK_m . Particularly, each register R_i has a control terminal, which is used to trigger the loading of the word supplied at its input (word IN for the register R_1 and word IN_i for the other

EXPRESS MAIL NO. EV343427580US

registers R₂-R₅). The first register R₁ and the last register R₅ are directly controlled by the main clock signal CLK_m. The other registers R₂-R₄ (of the intermediate stages ST₂-ST₄) are controlled by local clock signals CLK₂-CLK₄, respectively. The local clock signals CLK₂-CLK₄ are generated from the main clock signal CLK_m using a phase shifting circuit. This circuit has a delay block D_i for each intermediate stage ST_i. The block D_i generates the corresponding local clock signal CLK_i by applying a pre-set delay d_i to the clock signal controlling the next stage ST_{i+1}; in other words, the local clock signals CLK₂, CLK₃ and CLK₄ are generated by delaying the clock signals CLK₃, CLK₄ and CLK_m, respectively. The delay blocks D₂-D₄ ensure that the main clock signal CLK_m and every local clock signal CLK_i are out of phase, so that all of the registers R₁-R₅ never switch at the same time.

Similar considerations apply if the pipeline includes a different number of stages (down to three), if the word consists of a different number of bits, if the registers are replaced with equivalent buffers, if a further combinatorial circuit is connected to the last register, if the first register is missing, and so on.

Operation of the pipeline structure described above is shown in the simplified timing diagram of Figure 3. The various signals are switched at the rising edge of the respective clock signal (CLK_m, CLK₂-CLK₄); each word is represented by a band (the crossing points of the band define the switching times). The input word IN is loaded into the first register R₁ (word IN₁) at the time T₁ (in response to the rising edge of the main clock signal CLK_m). The word IN₁ is processed by the combinatorial circuit C₁; the output of the combinatorial circuit C₁ (word OUT₁) is stored in the second register R₂ (word IN₂) at the next rising edge of the local clock signal CLK₂ (time T₁+d₄+d₃+d₂). In a similar manner, the output of the combinatorial circuit C₂ (word OUT₂) is stored in the third register R₃ (word IN₃) at the next rising edge of the local clock signal CLK₃ (time T₂+d₄+d₃). The output of the combinatorial circuit C₃ (word OUT₃) is likewise stored in the fourth register R₄ (word IN₄) at the next rising edge of the local clock signal CLK₄ (time T₃+d₄). The word IN₄ is then processed by the combinatorial circuit C₄; the output

EXPRESS MAIL NO. EV343427580US

of the combinatorial circuit C_4 (word OUT_4) is stored in the last register R_5 (providing the output word OUT) at the next rising edge of the main clock signal CLK_m (time T_4). Therefore, three clock periods (T_1-T_4) are needed to pass through the entire pipeline (in order to get the output word OUT corresponding to the input word IN).

5 Correct operation of the pipeline requires that a new word cannot be written into a register before the previous one has been used (by the corresponding combinatorial circuit). Particularly, a generic word IN_i is supplied to the combinatorial circuit C_i as soon as it is loaded into the corresponding register R_i . The combinatorial circuit C_i generates the resulting word OUT_i after the respective propagation time P_i . In order to
10 ensure that the combinatorial circuit C_i has completed its work before the word OUT_i is stored in the next register R_{i+1} , the difference between the switching times of the registers R_{i+1} and R_i must be greater than the propagation time P_i of the combinatorial circuit C_i .

Considering in particular the first stage ST_1 , the register R_1 switches at every rising edge of the main clock signal CLK_m (for example, T_1); the second register R_2
15 switches at the time $T_1 + d_4 + d_3 + d_2 = T_1 + \sum_{j=2}^{N-1} d_j$. Therefore, the following relation

must be met:

$$T_1 + \sum_{j=2}^{N-1} d_j - T_1 \geq P_1$$

$$\sum_{j=2}^{N-1} d_j \geq P_1$$

20 Denoting with T_m the time of a generic rising edge of the main clock signal CLK_m , a register R_i of any intermediate stage (from ST_2 to ST_4) switches at the time $T_m + \sum_{j=i}^{N-1} d_j$;
the next register R_{i+1} switches at the time $T_{m+1} + \sum_{j=i+1}^{N-1} d_j = T_m + T + \sum_{j=i+1}^{N-1} d_j$ (where T is the

EXPRESS MAIL NO. EV343427580US

period of the main clock signal CLK_m). Therefore, the restraint applicable to every intermediate stage is:

$$T_m + T + \sum_{j=i+1}^{N-1} d_j - (T_m + \sum_{j=i}^{N-1} d_j) \geq P_i$$

$$T - d_i \geq P_i$$

5 Finally, the register R₄ switches at the time T₃+d₄ and the register R₅ switches at the time T₄=T₃+T, so that the following condition must be met for the last stage:

$$T_3 + T - (T_3 + d_4) \geq P_4$$

$$T - d_4 \geq P_4$$

Similar considerations apply if a different timing is envisaged for the pipeline, if
10 the signals are strobed after two or more clock periods from their switching, if the
difference between the switching times of the adjacent registers is greater than the clock
period, and so on.

More generally, the present invention proposes a pipeline structure for use in a
digital system. The pipeline structure includes a plurality of stages arranged in a
15 sequence from a first stage (for receiving an input of the pipeline structure) to a last stage
(for providing an output of the pipeline structure); one or more intermediate stages are
interposed between the first stage and the last stage. The first stage and the last stage are
controlled by a main clock signal. In the pipeline structure of preferred embodiments of
the present invention, phase shifting means or circuitry is provided for generating one or
20 more local clock signals (from the main clock signal) for controlling the intermediate
stages; the main clock signal and the local clock signals are out of phase.

The proposed solution greatly reduces the peaks of power consumption in the
pipeline structure. In this way, less sources of noise are introduced. Moreover, the
constraints in the design of a power supply structure for the whole electronic device that
25 embeds the pipeline are relaxed; particularly, metal tracks used to supply the electronic
device (when integrated in a chip of semiconductor material) may be smaller. As a
consequence, a reduced area of the chip is required to integrate the electronic device.

EXPRESS MAIL NO. EV343427580US

This result is achieved with a very simple architecture, without any handshaking mechanism being required between the stages of the pipeline.

In addition, the pipeline structure of preferred embodiments of the present invention maintains a synchronous interface with external circuitry (for the flux of input 5 and output information). Further, the proposed solution makes it possible to reduce the number of clock periods required to pass through the entire pipeline (compared with the conventional synchronous pipeline), even if different timings are not excluded.

The preferred embodiment of the present invention described above offers further advantages. For example, the preferred pipeline structure has multiple intermediate 10 stages, each one of which is controlled by a corresponding local clock signal (with all the local clock signals being out of phase). This feature further reduces the peaks of power consumption (since all the intermediate stages switch at different times).

Preferably, each local clock signal is obtained by delaying the clock signal controlling an adjacent stage.

15 The proposed structure is very simple, but at the same time effective.

As a further enhancement, each delay block preferably receives as input the clock signal of the next stage. This solution makes it possible to ensure correct operation of the pipeline with shorter delays (than if the local clock signals were obtained from the previous stage).

20 Alternatively, the local clock signals are not all out of phase, two or more stages are controlled by the same local clock signal, the pipeline includes a single intermediate stage, each local clock signal is obtained by delaying another clock signal (for example, the one controlling the previous stage), or different phase shifting means or circuitry are envisaged.

25 Preferably, each intermediate stage includes a functional unit and a buffer; the functional unit has a propagation time lower than the phase difference between the corresponding clock signal and the clock signal controlling the next stage. This structure

EXPRESS MAIL NO. EV343427580US

better exploits the advantageous effects of the present invention (at the same time ensuring correct operation of the pipeline).

Preferably, each stage consists of a combinatorial circuit and a corresponding buffer (storing a word). In this way, the peaks of power consumption are reduced to the 5 minimum.

However, the solution according to the present invention also leads itself to be implemented in a pipeline wherein each register consists of a stack with a depth of two or more words, or even in a pipeline having a different architecture (for example, consisting of a simple shift register without any combinatorial circuit).

10 Typically, the pipeline structure of the present invention is used in a digital system. The improvement provided by the synchronous interface of the proposed pipeline structure is clearly perceived in a digital system of the synchronous type.

Moreover, the solution according to the present invention is particularly advantageous in an electronic device that is supplied by a battery (wherein the power 15 consumption is a very critical issue).

However, the pipeline of the present invention is also suitable for use in different digital systems (even of the asynchronous type), and in any other electronic device (for example, supplied by an electric main).

While there has been illustrated and described what are presently considered to be 20 the preferred embodiments of the present invention, it will be understood by those skilled in the art that various other modifications may be made, and equivalents may be substituted, without departing from the true scope of the present invention. Additionally, many modifications may be made to adapt a particular situation to the teachings of the present invention without departing from the central inventive concept described herein. 25 Furthermore, an embodiment of the present invention may not include all of the features described above. Therefore, it is intended that the present invention not be limited to the particular embodiments disclosed, but that the invention include all embodiments falling within the scope of the appended claims.